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Julie Futcher[1], Gerald Mills[2], Rohinton Emmanuel[3]
[1]Urban Generation, London, UK;
[2]School of Geography, University College Dublin, Dublin, Ireland;
[3]School of Engineering and the Built Environment, Glasgow Caledonian University, Glasgow

ABSTRACT

Regulated energy loads of buildings are typically explored at the scale of individual buildings, often in isolated (and idealised) circumstances. By comparison, there is little research into the performance of building groups that accounts for the interactions between buildings. Consequently, the energy efficiency (or penalty) of different urban configurations (such as a city street) are overlooked. The research presented here examines the energy demand of a city street in London, which is comprised of typical office buildings with internal energy gains associated with a daytime occupancy. Simulations are performed for office buildings placed in urban canyons that are defined by ratio of building height (H) to street width (W). The results show the annual energy demand is dominated by the cooling load, which can be significantly reduced through street design that provides shading by increasing the H/W value. However, the 'best' street design for modern office buildings may be incompatible with that for residences or, for that matter, outdoor climates.

Keywords: Urban Canyon, Height to Width Ratio, Heating and Cooling Loads, Built Form, Urban Climate

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1. Introduction

The building sector accounts for approximately 20/40% of final energy consumption in developing/developed nations respectively (Perez-Lombard et al., 2008) and improving building energy efficiency is a key climate change mitigation strategy (IPCC, 2014). Building energy demands are conventionally divided into cooling and heating demands that are driven by time of day, season and occupation use that require different strategies. For example, while dwellings may have a strong morning/night-time demand, daytime energy need is greater in commercial buildings. Climate change projections for a warmer global climate (with greater frequency of warm days) indicate that the heating/cooling demand needs will change in the future (Isaac and Van Vuuren, 2009). Moreover, these changes will likely add to the urban heat island effect that takes place in cities where most buildings are located. As an example, the London response to climate change 'encourages the design of places and spaces to avoid overheating and excessive heat generation, and to reduce overheating due to the impacts of climate change and the urban heat island effect on an area wide basis'[1]. In this paper, we examine the energy performance of a street of modern office buildings in a temperate mid-latitude climate and the roles of climate and urban context as energy management parameters.

The typical approach to office energy management treats them as isolated standalone entities and uses thermal dynamic simulation tools and suitable weather files to simulate energy demand. The weather information is derived from a standard meteorological site, such as an airport, often located outside city centres. However, urban environments often experience a different diurnal and seasonal climate pattern to those located outside a city. These urban, non or semi-urban climate differences are becoming increasing acknowledged as important and building designers are encouraged, where possible, to account for these, either by using more suitable climate data or by altering the weather files representing a general 'background' condition to take account of urban effects (e.g. de la Flor and Dominguez, 2004; Chan 2011; CIBSE 2015).

To account for the energy performance of buildings in urban settings properly, the net impact of radiation exchanges, surface/air temperature (Giridharan et al, 2003; Rajagopalan et al 2008) and wind (Pisello et al., 2016) need to be considered. However, for a modern office building in which the internal climate is tightly managed through heating, ventilation and air conditioning (HVAC), the urban impact is generally considered to be small when compared to decisions on the building envelope and HVAC system itself (Moonen et al., 2012). As a result, many buildings in the urban landscape are designed to maximise their own energy efficiency performance without reference to the urban impact and the shared interactions between neighbouring buildings (Futcher et al., 2017). Yet, these mutual dependencies of buildings could yield heating/cooling benefits and/or penalties that are not accounted for when the energy performance of a neighbourhood is assessed. Moreover, these impacts are likely to depend on: the character of the urban neighbourhood, including building layout; built form including dimensions and materials; occupation and activity patterns that drive energy demand and; climate and weather variations at different timescales. While the relationship between the outdoor urban, and indoor building climates has been acknowledged (e.g. Taha et al., 1988; Papadopoulos, 2001; Santamouris et al., 2001, Moonen et al., 2012, Kolokotroni et al., 2012, Futcher et al 2013,) it is rarely considered or evaluated at urban scales.

This paper focuses on the impacts of built form on energy performance in commercial office buildings, which are driven by daytime occupation when external and internal energy gains are greatest and the

[1] London's Response to Climate Change, Chapter 5 available at https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-chapter-five-londons-response

cooling (rather than heating) load dominates. It uses the street as a fundamental urban spatial unit and examines the impact of street geometry (specifically, the H/W ratio) on energy demand over the course of the year using the thermal dynamic simulation tool IES Virtual Environment (IES<VE>). The simulations use weather data representing the generic climates for Glasgow and London and the urban climate of London to highlight the built form effect at neighbourhood scale against the background climate effects.

2. Literature Review

Evaluations of the effects of the urban built form on building energy performance remain scarce (Palme et al., 2017) partly because of the extreme spatial heterogeneity found in cities. Assessments at aggregate neighbourhood scale using empirical data (e.g. Yi and Peng, 2017; Lee and Lee 2014; Ko & Radke, 2014; Wilson, 2013; Ko, 2013) have not provided clear evidence for the energy benefits (or costs) of different urban layouts. For example, Li et al (2018) found that, for residential energy demand, urban building density and condition of dwelling type affect electricity consumption; while households in slab and tower apartments in dense urban neighbourhoods consume more electricity as neighbourhood density increases, the opposite was the case for single-family houses. In order to examine the relative roles of urban layout, building type, climate, etc. in urban energy performance controlled assessments are needed using key simplifying assumptions that have general application. Two methods that commonly used in the literature are to reduce the complexity of the urban context by focusing on buildings in common urban configurations and using a modified building thermal model (Malys et al., 2015). For example, Wong et al. (2010) simulated the energy performance of a single three-storey, air-conditioned warehouse/office building in the tropical climate of Singapore over one day. To represent different urban settings, thirty-two scenarios were examined by modifying: the proportion of the landscape that was vegetated; the heights of buildings and; the number of buildings (effectively increasing built density). The internal energy gains associated with office activities (lighting, computers, etc.) were not considered in the experiment. The results showed that increasing the heights of surrounding buildings at this latitude reduced cooling loads by up to 4.5%. Similarly, Lam (2000) simulated the performance of identical buildings, with and without shading, for Hong Kong (again without internal gains). For peak design conditions (at 3PM throughout July) the shaded building had a 14% reduction in cooling need. However, the urban street canyon is the most widely used framework across urban climate science and provides a viable approach for comparisons.

The urban canyon is defined as long street with an orientation (Ø) and the primary dimensions of building height (H) and of street width (W). It has served as a fundamental morphological unit in urban climate science (Oke et al., 2017) and provides a link between research on indoor and outdoor climate management. The ratio of height to width (H/W) has been shown to be an important urban parameter that can be linked to exchanges of energy, mass and momentum within the street (e.g. Arnfield 2003; Bourbia and Boucheriba 2010). The canyon model has been used to examine outdoor surface and air temperature, airflow patterns, street air quality and building solar access. As a consequence, H/W is a parameter that can be used to capture the urban effect on both outdoor urban and indoor building climates (e.g. Smith and Levermore, 2008). For example, Oke (1981) showed the available data on maximum urban heat island intensity (measured as the difference in near-surface air temperatures between urban and rural sites) is related to H/W. This maximum occurred at night, under clear skies and calm conditions when urban surfaces cooled more slowly than rural surfaces. Similarly, H/W has been used to study the heating and cooling energy performances of individual buildings in urban areas (e.g. Strømann-Andersen and Sattrup 2011; Wong et al 2010; Krüger et al. 2010) and to examine the thermal environment of pedestrians (e.g. Emmanuel et al., 2007; Ali-Toudert and Mayer 2006; Lin et al, 2010). However, the potential to use H/W as a parameter for evaluating energy performance at an urban scale, such as streets, has not been widely explored (Futcher et al., 2013).

Ali-Toudert (2009) examined the performance of a single building by modifying street design and building properties (thermal insulation and inertia, glazing ratio, etc.) in three different climate regions (mid-latitude, and subtropical hot-humid and hot–dry). Cooling needs decreased as streets narrowed in all three climates but the impact was greatest for hot-dry climates where cooling loads dominate. In the same vein, Krüger et al. (2010) found that the largest increases in cooling load occurred for streets with smaller H/W ratios (0.33) in a N-S oriented canyons, up to 250% more than the load for streets with high H/W ratios that were fully shaded. On the E-W orientation, an H/W ratio of 2.0 would yield a decrease in energy demand for cooling of up to 40% in the summer but, could significantly increase winter energy demand for heating. Finally, in a mid-latitude environment, Watkins et al. (2002) and Kolokotroni et al. (2006 & 2012) modelled the performance of an office building in different parts of London and in a rural environment. The cooling load was significantly lower for the rural setting (up to 50% lower) but even within the city, the load was influenced by the position of the building within the city, in particular the surrounding built density.

3. Methodology

This study focuses on the roles of climate and of different urban effects on energy performance of office buildings. The urban effects can be separated into direct (built form) and indirect (climatic); while the former describes the mutual shading and screening associated with radiative interactions between buildings, the latter describes the changes to air temperature, humidity and wind caused by urbanisation. The built form effects are evaluated by comparing the energy performances of office buildings in isolated and urban contexts using IES <VE> software. The impact of general climate and urban climate effects on performance are assessed using climate data from the design summer year (DSY) CIBSE weather files, which provide a range of weather variables for analysis from meteorological office weather stations. The DSY files capture the sequence of weather for warm years and are used to evaluate overheating risks for buildings and capture three scenarios: DSY1 is a year with a moderately warm summer; DSY2 has a summer with a short intense hot spell and; DSY3 has a summer with a long, less intense warm spell. TM49 (CIBSE 2014) recommends that all three DSY types are used to investigate the sensitivity of building energy demand to weather conditions.

Two UK cities are selected (London and Glasgow) and three DSY weather files are used, Glasgow, London Heathrow (London HR) and London Weather Station (London WS). The Glasgow and London HR files represent the latitudinal extent and the range of general climate variations across the UK. Although both cities have the same background climate type (Koppen Cfc type, that is, temperate, humid, cool summer; Kottek et al., 2006) there are differences, most obviously Glasgow has a smaller cooling load. The London HR and London WS files capture the same general climate but the latter represents the urban climate effect.

The role of building design is examined using two office building types, labelled A and B (Figure 2 and Table 1) in both a standalone and urban context. Appropriate building parameters are used to establish heating/cooling loads and internal gains that typify air-conditioned, open-planned office buildings in the UK. These benchmark values have been employed in several UK building energy management studies (e.g. Watkins et al., 2002; Kolokotroni et al., 2006a; Jenkins, 2009; Korolija et al., 2011, Futcher et al 2013). The impact of urban form is explored by placing buildings in rows to form eight different street canyon configurations (Figures 4 and 6). Both the building types and street canyons have identical floor, front surface and glazing areas, and internal gains, but are distinguished by the height and footprint of the two types (‘A’ has twice the footprint and, consequently half the height of ‘B’) and orientation based on the direction of the glazed façade (east or west, north or south).

The choice of building types and streets is based on Moorgate, a street in the City of London that consists of parallel rows of office buildings of equal height (Figure 1). It represents a near homogeneous micro-scale urban environment in terms of building type, occupation patterns and street design (e.g. Department of Planning & Transportation (2011) and Department of the Built Environment, City of London Corporation). Moorgate is comprised of high-end office buildings of similar height, volume and construction, typically seven stories tall (25m) with a gross floor area of approximately 15,000m^2. The surface finish is often masonry with a high percentage of glazed frontage; the glazed front of each building faces a street that is 20 m wide and has no vegetation. Each building on the street has occupation patterns and activity levels that correspond to office activities during the working day.

In the text that follows, orientation is identified using a subscript, for example A_E is a type A building with the glazed façade oriented to the east. Building types A and B were first simulated in a standalone setting (that is, with no neighbouring buildings) to obtain reference loads. These reference loads are then compared against the performance of the identical building forms within different street canyons, distinguished by two properties, H/W ratio and orientation (Ø), and located in two UK cities. All simulations are run using the standard building parameters (Table 1) which allows us to focus on the relative roles of climate, urban climate and built form on energy performance. These simulations represent an initial design stage analysis and we do not evaluate any subsequent optimisation such as modifications to the glazed façade to improve performance that may be considered.

3.1 Simulation Software

Virtual Environment (VE) by IES Ltd. is used as a design tool to estimate the energy performance of buildings throughout all design stages, however here it is used to evaluate building energy performance for multiple buildings arranged along a city street. Other studies have used tools such as ENVI-met to examine urban effects (see Salata al., 2017 for a review) but it is designed chiefly to look at outdoor climate conditions under specified conditions and for a limited time scale (24-48 hrs) rather than building energy use over longer periods. VE has been used for various urban energy management studies (e.g. Strømann-Andersen and Sattrup 2011; Kolokotroni, et al., 2012; Futcher et al., 2013) and has been validated in accordance with both CIBSE TM33 2006 and ANSI/ASHRAE 140-2007 standards.

3.2 The role of Internal Gains

Research has shown that for office buildings, internal gains are a significant driver of cooling loads (Lam 2000; Voss et al., 2006; Jenkins, 2009). However, cooling loads are also influenced by other parameters including the levels and timings of the activities, the building design (envelope, surface to volume ratio etc.), and, the background climatic or weather conditions. Consequently, a change in either activity or background conditions results in identical building performing differently (Kolokotroni, et al., 2012; Futcher et al., 2013).

Simulations were run for the two building types (A and B) with and without internal gains, using the three DSY files. Only the results for the east-facing type 'A' building (A_E) are shown (Figure 3) as they are representative both of building types and orientation - more details of heating and cooling loads are shown in Figure 5. Figure 3 indicates that internal energy gains are the dominant factor for determining both heating and cooling demands for all climate scenarios, although the background conditions are also shown to have an impact. As expected, heating demand in Glasgow is greater than that in London, and cooling demand in London is greater. However, we can see similar patterns in performance that relate to the weather. For example, the cooling load for Glasgow DSY1 (2003), London Heathrow and London Weather Station DSY2 (2003) follows similar trends between June and September, with Glasgow's demand with internal gains a) being similar to London's demand without internal gains b). Even the slight uplift in demand for April is picked up for both cities. Also, as expected the length of the cooling season is longer for London (February to November) than Glasgow (March to October) for 2003. Although for London with a) internal gains, the winter time heating load becomes negligible, with over 90% of the annual cooling load is driven by internal gains. In the remainder of this paper all simulations include internal gains.

3.3 Street Configurations

The impact of variations in street properties on building performance are examined by arranging 'A' and 'B' along 8 street canyons (labelled C1 to C8). Each street canyon is comprised of parallel rows of buildings, each with its glazed façade facing toward the street (Figure 4). Each 'A' and 'B' types is placed at regular intervals along the length of the street so that each canyon is formed of a different number of buildings. For each canyon studied here, the results for eight buildings (four on each side of the canyon) are presented so that the total canyon floor area and front surface area and area of glazing are constant. The street canyons C1 to C8 represent a variety of realistic urban settings; C1, which is comprised of a series of A buildings arranged as a terrace without gaps, is modelled on present day Moorgate. The other street canyons are variations on this theme.

All street canyons are parallel rows of the same length (240 m) and width (20 m) within the VE modelling environment. Each building in the study can be identified by its canyon type (C1 to C8) its form (A or B), its position within the canyon (1-8) and the orientation of its glazed façade – the latter is based on the side of the street and street orientation (Figure 2 & 4 and Table 3). To account for the urban environment outside the canyon under study, a parallel row of buildings (type A) is included in simulations. Similarly, at either canyon end a building was placed along the same street axis at a 15 m separation. All canyons apart from C1 have infill buildings. Whilst these infill buildings are included in the simulations, their energy loads are excluded from the results. All buildings that represent the boundary conditions can be identified as the non-shaded or pale buildings.

Initially the street axis for these canyons is oriented north-south (N/S) so that the glazed surfaces of the buildings on the east-side face west and vice versa. A separate set of simulations are performed using an east-west (E/W) street axis. Simplifying the urban environment in this way allows us to examine the energy performances of individual buildings and of the whole street while modifying street geometry.

4. Results

Monthly simulations were performed to assess the energy demands of all buildings in both their standalone (reference) and canyon settings. Figure 5 shows the annual cooling demand (kWh/m2/yr) for building types A and B, oriented in each of the cardinal directions, in the standalone context. All assumptions are in line with the UK energy benchmark guidelines for office building types (ECG 19, 2000). It is important to re-iterate here the need to evaluate the timing of the urban climate effects in relation to the timing and nature of the building occupancy. The present study explores daytime office activities which coincide with solar gain which often results in a dominant daytime cooling load. These relationships can also be identified in cooler climates such as Glasgow. It is worth noting that during the day urban air temperatures are often the same or lower than their non-urban surroundings due to the interception of the solar beam and their greater capacity to store energy – so called 'cool island' effect (Emmanuel and Kruger, 2012). These lower daytime air temperatures are reflected in the results where the cooling load for the London WS is similar if not ever so slightly lower than those of the identical buildings in London HR (Figure 5).

Glasgow's demand differences aside, the lowest cooling demand always occurred for those building facing north, which admitted the least solar energy through the glazed façade (13, 32 and 32 $kWh/m^2/yr$). Not surprisingly, the south-facing building had the greatest demand for cooling (16, 60 and 62$kWh/m^2/yr$) with the east- and west-facing buildings having demands between these extremes. On the other hand, the heating demand showed little dependency on orientation; although south-facing buildings showed a slightly reduced demand, and types A had a slightly higher cooling (<2 kWh/m2/yr), and heating (<1 kWh/m2/yr) demand, regardless of background conditions, in every case, which could reflect the slightly higher total surface area of type A over type B.

The low heating demands shown here are a result of climate effects (as seen from a comparison of heating demand for Glasgow vs. London WS, which in the case of DSY1 up to 88% lower). Additional effects due to the building envelope fabrication (including percentage of overall glazing), the length of the heating season, the established set-point temperature, the low number of air changes per hour and the level and timing of the internal gains would add further differences but are not studied here. Once again it is important to emphasise that the internal gains occur during the same period as the solar heating effect, which emphasises the significance of minimizing daytime climate driven loads. This is clearly seen in the case of London which has a significantly higher cooling load than Glasgow (165% higher DSY1 [A-S])

4.1 The Energy Performance of Buildings in Streets

Figure 6 shows a 'map' of the buildings and canyons used in the energy simulations. Each building is coded according to its place in the street (C1 to C8) and its type (A of B). These codes (e.g. C7, 4A) are used to identify the energy performance of individual buildings. The canyons are oriented north-south, so that the buildings in each are oriented east or west. Canyons C1 and C2 are comprised entirely of A (H/W of 1.2) and B (H/W of 2.4) buildings creating a symmetric profile along its length, while the other canyons with combinations of A and B buildings have asymmetric profiles. Figures 7, 8 and 9 (and Tables 4) show the annual cooling and heating loads of A and B using the Glasgow and London weather files. These loads can be compared against the standalone reference values shown in Figure 5. All experience a reduction in solar energy gain as a result of the built form effect, which provides mutual shading. Figure 7 shows the output performance for all eight canyon configurations for the three Glasgow DSY weather files; Figures 8 and 9 show the same information London HR and London WS, respectively. Note that built form effects dominate for these types of buildings with daytime functions, the urban climate effect (including the urban heat island) has a minimal effect.

The performance of the buildings at the centre of the terraced C1 arrangement had slightly higher loads than those at the canyon ends; these buildings have an additional exposed façade, which the terraced buildings do not. An overall reduction between 10 and 15 % for the Glasgow cooling loads was noted for the C1 street canyon form (or 3 kWh/m2/yr); differences in heating loads were much lower (less than 1 kWh/m2/yr). Similar performance patterns in cooling loads for C1 were noted for the London climate files, where the average cooling loads dropped from around 50 kWh/m2/yr to around 40 kWh/m2/yr when compared to the reference values (Figure 5, 8 and 9), this reduction was more or less equal for all buildings in the C1 configuration. A similar pattern but higher magnitudes of cooling load reduction occur for the C2 configuration, which has the higher H/W ratio and greater levels of shading.

The output performance patterns of the asymmetrical streets, which have a row of type A buildings opposite type B buildings and vice versa (C3 and C4) shows the clearest effect of shadowing. The lower buildings (A) experience dramatic improvements in their energy demands as a result of the taller buildings shading either morning or afternoon sun, while the taller buildings (B) lose much of the advantage experienced in the C2 configuration. These graphs show the consequence of reduced solar obstruction to the upper half of the surfaces of B, alongside the significance of shading for the walls and roof surfaces of A. Buildings in canyons C5 to C8, which consist of a mixture of A and B along each side of the street have a mean H/W of 1.8. While the overall effect of the street is to improve performance, the benefits for individual buildings vary greatly depending on their specific interaction with the neighbouring buildings.

The effect of mutual shading is best illustrated by looking in greater detail at monthly cooling demands for all buildings arranged along their different street canyon configuration. Here we present the results of C8 only as it is representative of the average performance of the mixed arrangements C5 to C8 (Figure 10). The graphs show monthly cooling loads as the difference in MWh against the equivalent standalone reference building. Here we focus on buildings 5A & 6A, which are identical and adjacent to each other, yet the differences in demand reflects the slightly different relationship they have with their neighbouring buildings.

Again, despite the obvious differences in latitude and Glasgow having a cooler climate than London the largest difference occurs when cooling demand is greatest (March to September), and reflects the background conditions, although similarities between Glasgow DSY 1 (2003) and the DSY 2 (2003) scenarios for London picked up in the earlier section looking at the standalone building are lost here. A difference in cooling during the peak summer is clearly identified in all scenarios. The results demonstrate the importance of built form on the cooling demand of an office building and potential for street parameters to be used as indicators of energy management performance. Note that the differences between using the DSY files for London HR and WS were marginal, indicating that for office buildings driven by daytime use, urban built form effects are more significant that urban climate effects.

4.2 The Energy Performance of Streets

The approach used here allows one to examine the energy performances of the streets as a whole, rather than those of individual buildings. The accumulated cooling load for all the buildings in the street are compared with that for the equivalent number of stand-alone, reference, buildings in Figures 11, 12 and 13. The results correspond to H/W values: C1 with the smallest H/W (1.2) has the highest cooling load; C2 with the largest H/W (2.4) has the lowest cooling load and; C3-C8 with mean H/W values of 1.8 have intermediate cooling loads. These results are consistent with urban climate research that shows higher H/W values correspond to lower daytime temperatures on building and street surfaces. As an urban climate parameter, H/W determines the level of solar shadowing and consequently affects building energy gain and conditioning loads.

Up to this point, the study has focussed on configurations oriented on north-south street axis where access to solar radiation is symmetric around the canyon axis and both sides of the street are assured access to sunlight. Figures 11, 12 and 13 shows the overall results for streets oriented north-south (N/S) and east-west (E/W). In an E/W orientation, the north-facing buildings glazed façades are in permanent shade. Not surprisingly, these buildings show the least reduction in cooling loads and experience little benefit from their urban location. By comparison, the south-facing buildings get the greatest benefit from the shade provided by the buildings opposite. Overall however, the results for the streets as a whole follow the same pattern: C1 (H/W =1.2) shows the lowest urban impact; C2 (H/W =2.4) shows the highest and; C3 to C8 (H/W =1.8) falls between these extremes. The monthly patterns shown in Figures 11-13 illustrate the effect of both climate and of street design over the course of a year as the properties of the buildings are held constant. Note that the range of performance over the course of a year is greater for the streets-oriented N/S than those oriented E/W, which exhibit little seasonal variation. This is due to the solar path, which has a greater impact on the glazed east- and west-facing surfaces of streets.

An important observation is that the range of results between Glasgow and London appear similar when these are expressed as percentages of the differences from the baseline (Table 4). Given that these percentage differences are similar regardless of background climate conditions, it may be necessary to explore the relative contributions of latitude and elevation

5. Implications

The results have implications for types of city streets that are best suited to managing energy demand in modern office buildings, which are primarily driven by the need for cooling to offset external and internal energy gains. This need exists throughout the year but is greatest during the summer months when the interception of solar radiation adds to the energy load (Figure 5). By comparison, there is a minimal heating load in the winter months. The street with the highest H/W value performed the best of all the canyon types examined, regardless of orientation. Given that the street width is fixed, this implies that increasing the heights of buildings generally will reduce the cooling load. For the street with the lowest mean H/W ratio examined here (C2) annual reductions of 8-10% in the cooling demand were achieved. For these buildings there is an advantage to being located in dense built environments where the shading provided by other buildings reduces external heat gain. Reducing the built form effect by reducing H/W offers little advantage to these type of buildings. For the lowest H/W value examined here (C1) E/W streets provided no significant built form effect although the performance was somewhat improved for N/S streets.

For streets with higher H/W values (C2-C8) a uniform and symmetric cross-section is best. In these cases, the urban advantage is evenly shared among all buildings in the street. This is most evident in C2 when oriented N/S (Figure 6) but is also present when streets are oriented E/W (Table 4). For streets that are uniform along a side but are asymmetric in cross-section there is a clear advantage accruing to the shorter buildings on one side of the street. In N/S streets, these buildings get the advantage of the shade cast by the taller buildings in the morning or afternoon but the largest difference occurs when the street is oriented E/W and taller buildings are placed on the north side providing shade to lower buildings on the south side.

This work shows that increasing the H/W of streets that are dominated by typical commercial office space is beneficial as timing of its use (maximum internal energy use) and shading provided by built form (reduced external energy gain) correspond. This temporal correlation of internal energy use and external energy gain is nearly reversed for residential buildings where energy demand is greatest in the morning and evening hours. For mixed use buildings and streets, the energy demand is more evenly distributed during the day and energy demand may depend on the vertical distribution of space such as, for example, office space at ground level and residence above. It follows that higher H/W values may not be best for all buildings uses. Moreover, the energy performance of buildings should not be the only guiding principle for street design, as H/W exerts a strong control on outdoor climates including wind and pollution dispersion. In mid-latitude climates Oke (1988) suggested that H/W≈0.6-

0.8 represented the best ‘overall’ design for outdoor climates, including access to solar energy, potential for heat island generation, wind shelter and dispersal of street level pollutants.

6. Summary & Conclusions

The methodology here simulates the daytime urban effect on the regulated energy performances of individual buildings and building groups. To allow comparison, the energy demands of two building types, representing typical modern commercial offices were exposed to the same weather conditions. Importantly, these types of buildings are occupied during the daytime and have significant internal energy gains. To compare urban settings a street in central London was used to generate distinctive street configurations.

In an isolated (standalone) setting with unobstructed access to the available solar radiation, each building type has nearly identical energy performance regardless of their orientation (based on the direction that the glazed facade faced). However, in an urban context where neighbouring buildings provide shade, these performance patterns change significantly, and results show identical building to perform differently as a result of even small changes in their surround setting. In short, for occupied office buildings for which the cooling load dominates, improved energy performance is related to the shade provided by the neighbouring buildings, that is, the built form effect. At the scale of the city street, this effect is captured by the ratio of building height (H) to street width (W) and H/W is a useful measure of the energy performance of individual buildings and of streets in cities. Although these improvements may be considered small for individual offices, the accumulated effect for all the buildings in the street is considerable. The 'best' canyon design from this perspective is narrow in cross-section, H/W>2 and oriented north-south.

This study highlights the importance of perspective in studying the timing of the urban effects in relation to building/street use before identifying the 'best' urban design. Modern office buildings, even in the cool, high latitude, maritime climate studied here, require cooling during the daytime period when it is occupied and functioning. For these building types, which often comprise entire streetscapes (such as Moorgate), the best design is one that maximises solar shade on the street facade. However, for other street uses (both indoor and outdoor) this may not be suitable. This result cautions against simple criteria that seek to minimise the urban heat island effect for example by widening streets – in the current context this would increase energy demand for office buildings. Finally, we might consider the implications where the functions of a place change, even as the street form remains unchanged. The results presented here suggest that asymmetric streets, oriented E/W are most adaptable. The taller buildings (B) that currently face south could be adapted to residential needs, while still providing shade for the lower buildings (A), which should remain as offices.

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Table 01: Building properties for Form A and B

Building Properties	Form A	Form B
Floors above ground	7	14
Net Total floor area (m^2)	4000	4000
Building Footprint (m^2)	600	300
Building Height (m)	24.5	49
Width (m)	10	10
Length (m)	60	30
Surface area front face(m^2)	1470	1470
Surface area roof (m^2)	600	300
Surface area total (m^2)	8855	8470
Volume (m^3)	14700	14700
U-values (W/m^2K) - UK Building Regulations L2A-2016		
Flat Roof (Bitumen & stone chippings)	0.25	
External / Party Wall (Masonry)	0.35/ 0.2	
Floor	0.25	
Window/SHGC	2.2 /0.637	
OCCUPANCY PROFILE	Class Use B1 (Office)	
persons/m^2 *	0.1	
Occupation hours (holidays are treated as a working day)	7:30 am & 19:30 pm working week only, weekends are not included	
internal gains ($kWh/m^2/yr$)	78	
Heating set point/ set back (°C) (CIBSE 2006) **	19-/12	
Cooling set point/ set back (°C) (CIBSE 2006)	23/28	

Table 02: description of the arrangement of the 2 building forms in the eight canyon configurations

Canyon No.	Mean H/W	Building Form
C1	1.2	A
C2	2.4	B
C3	1.8	B opposite A
C4	1.8	A opposite B
C5 -C8	1.8	Mixed arrangement (A & B)

Table 03: Building form and orientation of glazed façade within each street orientation

Street Reference	North-South oriented								East-West oriented							
	East facing				West facing				North facing				South facing			
Building No.,	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
C1 H/W 1.2	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*
C2 H/W 2.4	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*
C3 H/W 1.8	*B*	*B*	*B*	*B*	*A*	*A*	*A*	*A*	*B*	*B*	*B*	*B*	*A*	*A*	*A*	*A*
C4 H/W 1.8	*A*	*A*	*A*	*A*	*B*	*B*	*B*	*B*	*A*	*A*	*A*	*A*	*B*	*B*	*B*	*B*
C5 H/W 1.8	*B*	*B*	*A*	*A*	*B*	*A*	*B*	*A*	*B*	*B*	*A*	*A*	*B*	*A*	*B*	*A*
C6 H/W 1.8	*B*	*A*	*B*	*A*	*A*	*B*	*A*	*B*	*B*	*A*	*B*	*A*	*A*	*B*	*A*	*B*
C7 H/W 1.8	*B*	*A*	*B*	*A*	*A*	*B*	*A*	*B*	*B*	*A*	*B*	*A*	*A*	*B*	*A*	*B*
C8 H/W 1.8	*B*	*B*	*A*	*A*	*A*	*A*	*B*	*B*	*B*	*B*	*A*	*A*	*A*	*A*	*B*	*B*

Table 4: Tabulated heating and cooling load data (kWh/m2/yr) for Figures 7–9, including the reference buildings

		DSY	C1								C2								C3								C4								REF	
			East				West				East				West				East				West				East				West				East	
			1A	2A	3A	4A	5A	6A	7A	8A	1B	2B	3B	4B	5B	6B	7B	8B	1B	2B	3B	4B	5A	6A	7A	8A	1A	2A	3A	4A	5B	6B	7B	8B	[A	[B
Cooling	Glasgow	1	18	18	18	18	18	19	19	18	15	15	15	15	15	15	15	16	18	18	18	18	15	16	16	15	15	16	16	15	18	18	18	18	21	20
		2	18	18	18	18	18	19	19	18	16	15	15	16	16	16	16	16	18	18	18	18	16	16	16	16	16	16	16	16	19	19	19	19	21	20
		3	19	19	19	19	19	20	20	19	16	16	16	17	17	16	16	17	19	19	19	19	16	17	17	17	16	17	17	16	20	20	20	20	22	21
	Heathrow	1	39	39	39	39	38	39	39	39	33	33	33	35	33	33	33	34	43	42	42	43	31	31	31	31	31	31	31	32	41	41	41	42	51	50
		2	41	42	42	42	41	42	42	42	36	36	36	38	36	36	36	37	46	45	45	46	33	34	34	34	33	34	34	34	44	44	44	45	52	50
		3	39	39	39	39	38	39	39	39	34	33	33	35	33	33	33	34	43	42	42	43	31	31	31	32	31	31	31	32	41	41	41	42	50	49
	London WS	1	39	40	40	40	39	40	40	40	34	34	34	36	34	34	34	35	43	43	43	44	31	32	32	32	31	32	32	32	42	42	42	43	51	50
		2	41	42	42	42	41	42	42	42	36	36	36	38	36	36	36	37	46	45	45	46	33	34	34	34	33	34	34	34	44	44	44	45	54	53
		3	39	39	39	39	38	39	39	39	34	33	33	35	33	33	33	34	43	42	42	43	31	31	31	32	31	31	31	32	41	41	41	42	50	49
Heating	Glasgow	1	12	11	11	12	12	11	11	12	12	12	12	12	12	12	12	12	11	11	11	11	12	12	12	12	12	12	12	12	11	11	11	11	11	11
		2	10	10	10	10	10	10	10	10	11	11	11	11	11	11	11	11	10	10	10	10	11	11	11	11	11	11	11	11	10	10	10	10	10	9
		3	12	12	12	12	12	12	12	12	13	13	13	13	13	13	13	13	12	12	12	12	13	12	12	13	13	12	12	13	12	12	12	12	12	11
	Heathrow	1	5	5	5	5	6	5	5	5	6	6	6	5	6	6	6	6	4	4	4	4	6	6	6	6	6	6	6	6	5	5	5	5	4	4
		2	6	6	6	6	6	6	6	6	7	7	7	6	7	7	7	7	5	5	5	5	7	7	7	7	7	7	7	7	6	6	6	6	5	4
		3	8	8	8	8	8	8	8	8	9	9	9	9	9	9	9	9	7	7	7	7	10	9	9	9	10	9	9	9	8	8	8	8	6	6
	London WS	1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	5	5	5	5	5	5	5	5	3	3	3	3	3	2
		2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	6	6	6	6	6	6	6	6	5	5	4	4	4	3
		3	7	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	6	6	6	6	8	7	7	8	8	7	7	8	6	6	6	6	5	5

		DSY	C5								C6								C7								C8								REF	
			East				West				East				West				East				West				East				West				West	
			1B	2B	3A	4A	5B	6A	7B	8A	1B	2A	3B	4A	4A	6B	7A	8B	1B	2A	3B	4A	5A	6B	7A	8B	1B	2B	3A	4A	5A	6A	7B	8B	[A	[B
Cooling	Glasgow	1	16	17	16	17	15	16	18	17	17	16	16	17	16	18	16	18	18	16	17	16	16	17	16	18	18	18	17	15	16	17	18	18	22	20
		2	16	18	16	17	16	17	18	18	17	17	17	17	16	18	16	18	18	16	18	16	17	18	17	19	18	18	17	16	17	18	19	18	22	21
		3	17	19	17	18	17	18	19	19	18	18	18	18	17	19	17	19	19	17	19	17	18	19	18	20	19	19	18	17	18	19	20	19	23	22
	Heathrow	1	36	42	33	38	33	35	41	37	38	36	38	38	33	40	33	40	42	33	42	33	35	39	35	41	43	43	38	32	35	38	41	41	48	47
		2	38	45	36	41	36	38	44	40	41	39	40	41	36	43	36	43	45	36	44	36	38	42	38	44	46	46	41	35	38	41	44	44	49	48
		3	36	42	33	38	34	35	41	37	38	36	38	38	34	40	34	40	42	33	41	33	35	39	35	41	43	43	38	32	36	38	41	41	47	46
	London WS	1	36	42	34	38	34	36	42	38	39	37	38	39	34	41	34	41	43	34	42	34	36	40	36	42	43	44	39	33	36	39	42	41	49	47
		2	38	45	36	41	36	38	44	40	41	39	40	41	36	43	36	43	45	36	44	36	38	42	38	44	46	46	41	35	38	41	44	44	51	50
		3	36	42	33	38	34	35	41	37	38	36	38	38	34	40	34	40	42	33	41	33	35	39	35	41	43	43	38	32	36	38	41	41	48	47
Heating	Glasgow	1	12	11	12	12	12	12	11	12	12	12	12	12	12	11	12	11	11	12	11	12	12	12	12	11	11	11	12	13	12	12	11	11	11	11
		2	11	10	11	11	11	11	10	11	10	11	10	11	11	10	11	10	10	11	10	11	11	10	11	10	10	10	11	11	11	11	10	10	10	9
		3	12	12	13	13	13	13	12	13	12	13	12	13	13	12	13	12	12	13	12	13	13	12	13	12	12	12	13	13	13	13	12	12	12	12
	Heathrow	1	5	5	6	6	6	6	5	6	5	6	5	5	6	5	6	5	5	6	5	6	6	5	6	5	4	4	6	6	6	6	5	5	5	4
		2	6	6	7	7	7	7	6	7	6	7	6	6	7	6	7	6	6	7	6	7	7	6	7	6	5	5	7	8	7	7	6	6	6	5
		3	8	8	9	9	9	9	8	9	8	9	8	8	10	8	10	8	8	9	8	9	9	9	9	8	7	7	9	10	9	9	8	8	7	7
	London WS	1	4	3	4	4	4	4	3	4	4	4	4	4	5	4	5	3	3	5	3	4	4	4	4	3	3	3	4	5	4	4	4	4	3	3
		2	5	4	6	5	5	5	4	5	5	6	5	5	6	5	6	4	4	6	4	5	6	5	5	4	4	4	5	6	5	5	5	5	4	4
		3	6	6	7	7	7	7	6	7	7	7	7	7	8	6	8	6	6	8	6	7	8	7	7	6	6	6	7	8	7	7	6	7	6	6

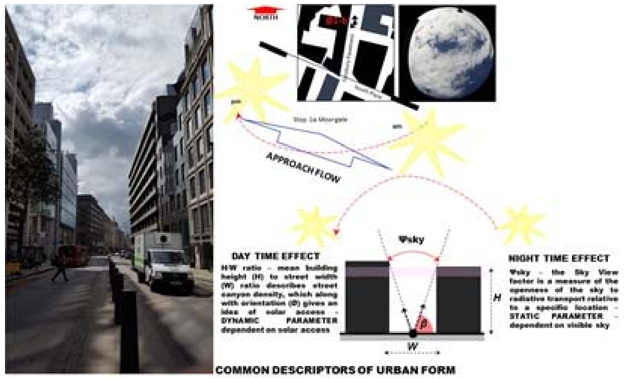

Figure 1: Looking south along Moorgate.

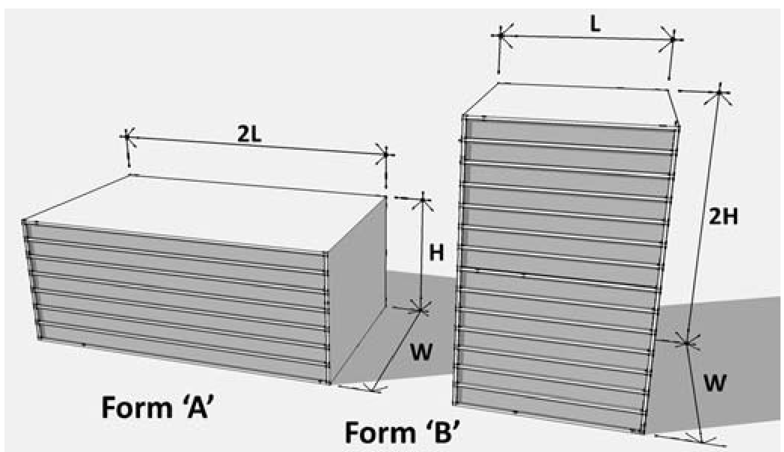

Figure 2: Geometric dimensions for the 2 Office building types A and B. Whilst both types have equal front surface area and areas of glazing, A has twice the footprint of B, which has twice the height of A

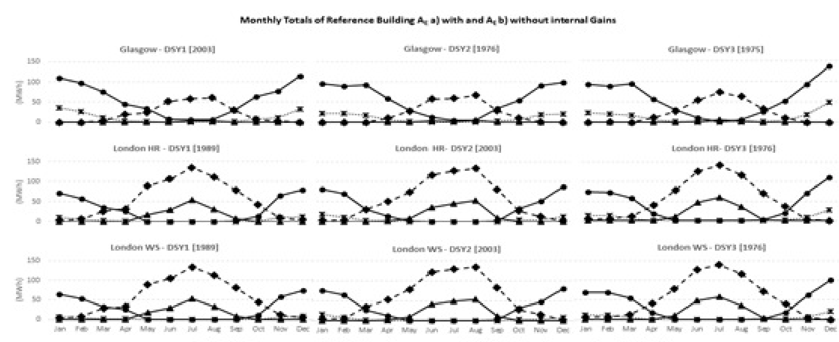

Figure 3: Heating and cooling loads (MWh) as monthly totals for building type A_E with (a) and without b) internal gains, for Glasgow, London Heathrow and London Weather Station Design Summer Year (DSY) 1, 2 and 3.. Internal gains are set at 78 kWh/m^2/yr

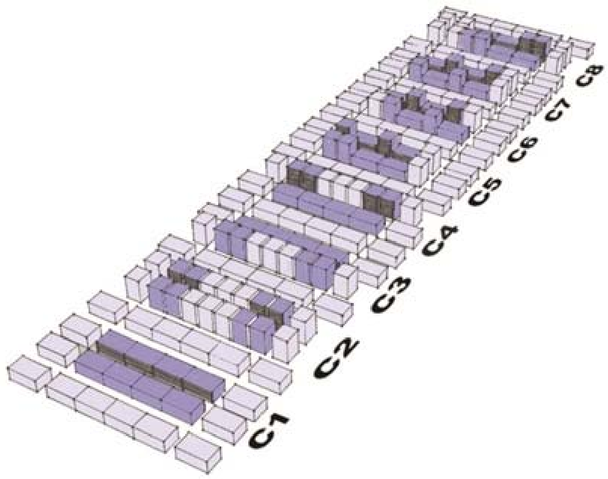

Figure 4: Geometric arrangement for the 2 Office building forms (A and B) along the 8 urban canyons C1 to C8; Each building can be identified by its canyon number [C1-C8], building reference number [1-4] East facing, [5-8] west facing and building form [A or B]. The non-shaded or pale buildings represent the boundary conditions i.e. the surrounding system and infill buildings

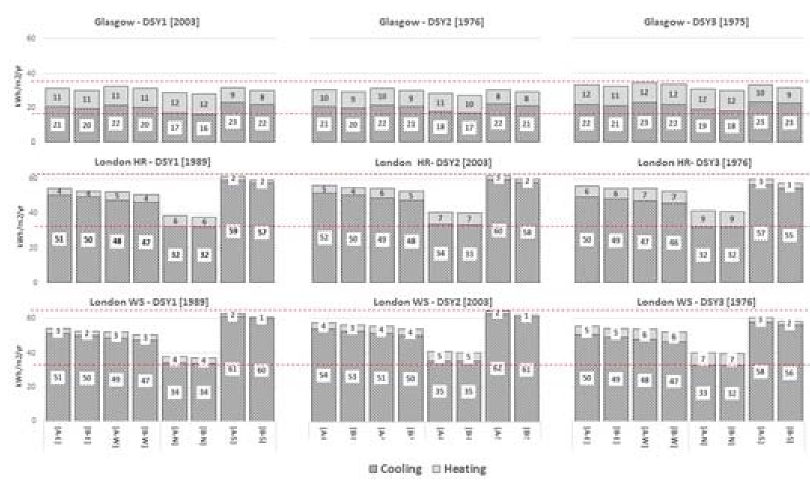

Figure 5: Cooling and heating loads (kWh/m²/yr) for standalone reference buildings type A and B with glazed façade oriented in four cardinal directions (East, West, North and South)

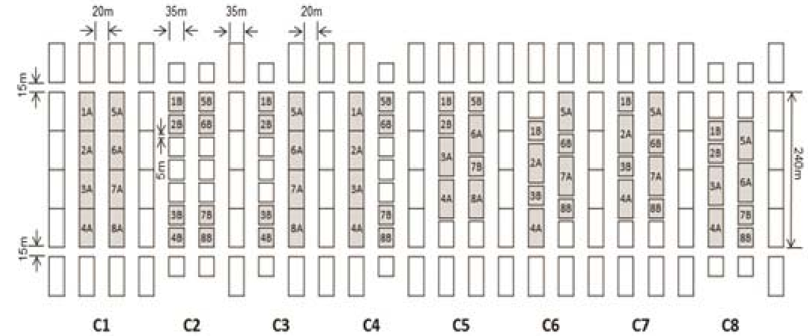

Figure 6: Identification layout of all buildings within their urban configuration. Each building can be identified by its canyon number [C1-C8], building reference number [1-4] east facing, [5-8] west facing and building type [A or B]. The non-shaded buildings represent the boundary conditions i.e. the surrounding system and infill buildings

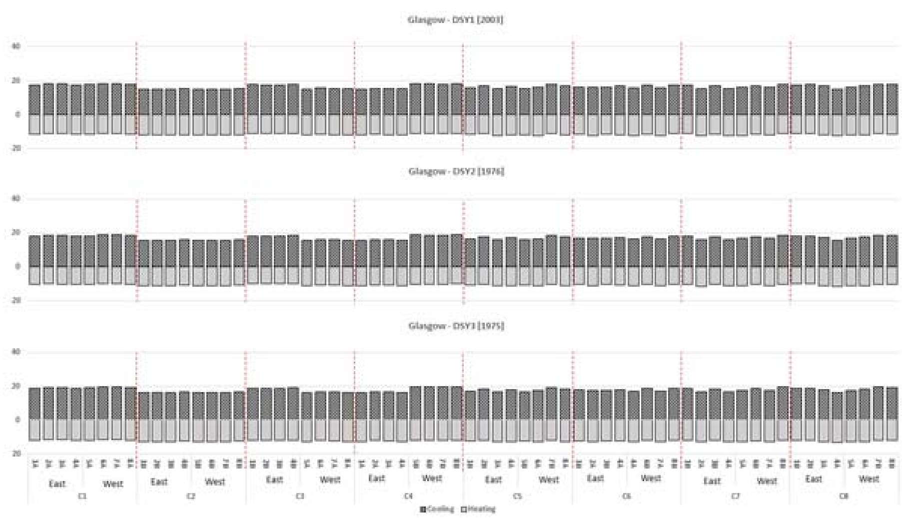

Figure 7: Output performance for all buildings in their 8-street canyon configurations (C1 to C8) for the 3 Glasgow DSY weather files (east and west facing buildings only) in kWh/m²/yr

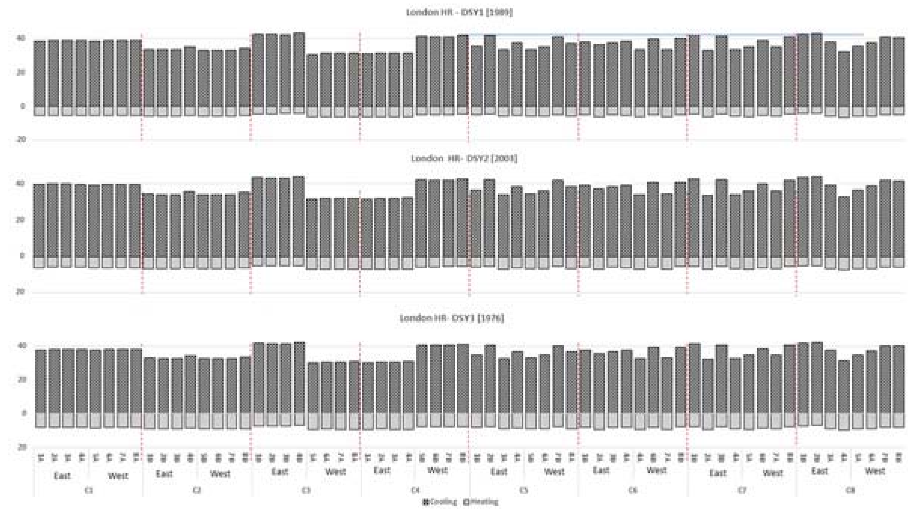

Figure 8: Output performance for all buildings in their 8-street canyon configurations (C1 to C8) for the 3 London Heathrow DSY weather files (east and west facing buildings only) in kWh/m^2/yr

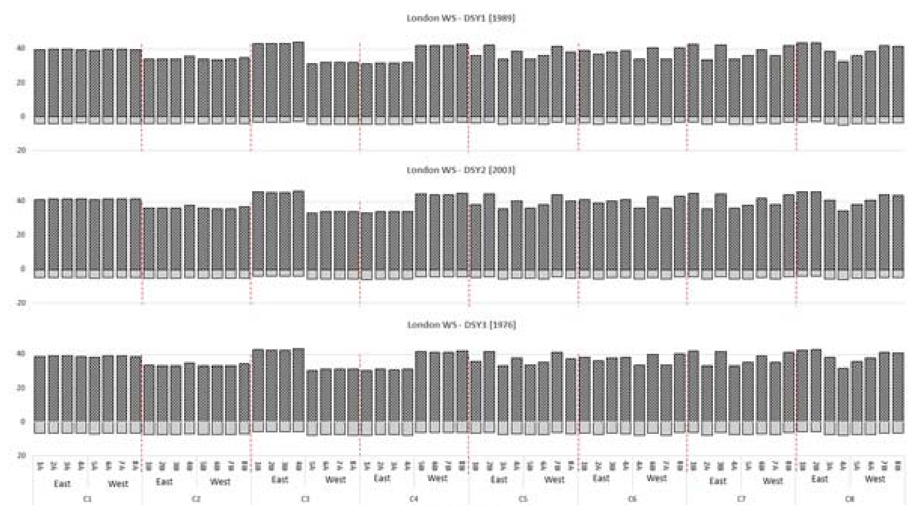

Figure 9: Output performance for all buildings in their 8-street canyon configurations (C1 to C8) for the 3 London Weather Station DSY weather files (east and west facing buildings only) in kWh/m^2/yr

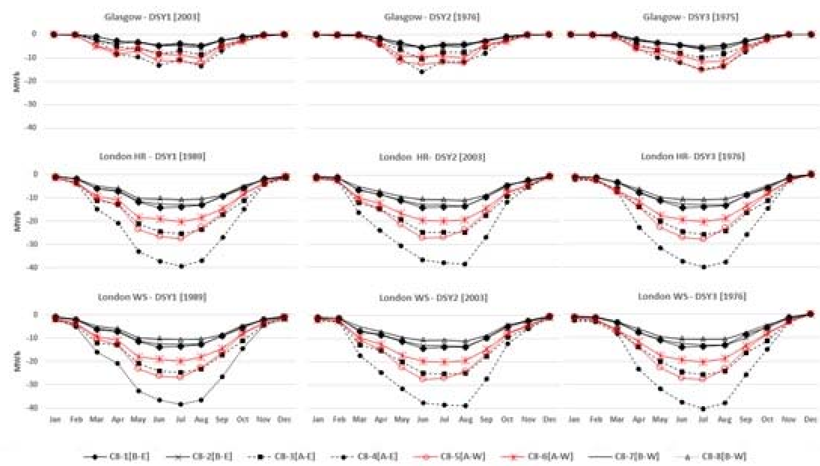

Figure 10: Monthly cooling demand difference between buildings contained within C8 against equivalent reference building

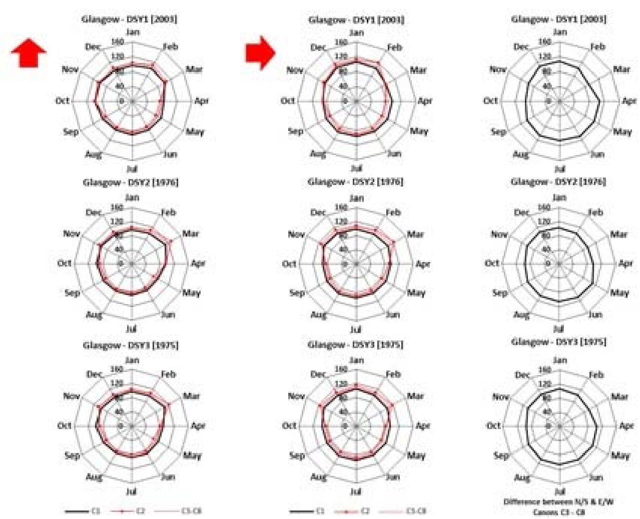

Figure 11: Monthly cooling loads for C1 to C8 for the North South orientated canyons (column 1), the East West orientated canyons (column 2), and the difference between these (column 3), for the Glasgow DSY weather files; C3-C8* are given as the average. Results are presented as the % difference against the equivalent standalone reference building

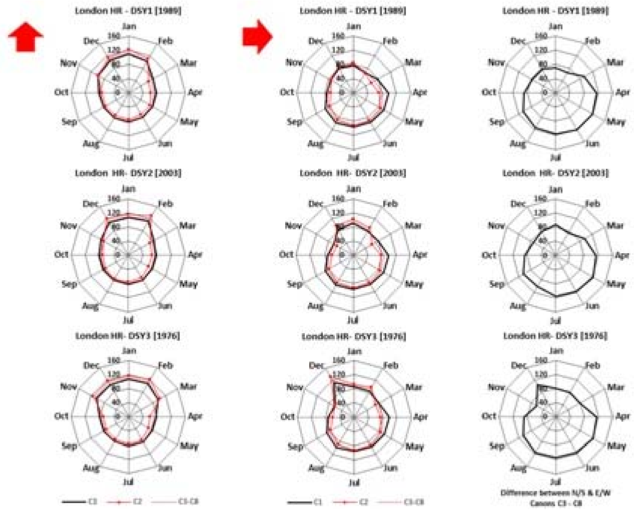

Figure 12: Monthly cooling loads for C1 to C8 for the North South orientated canyons (column 1), the East West orientated canyons (column 2), and the difference between these (column 3), for the London Heathrow DSY weather files; C3-C8* are given as the average. Results are presented as the % difference against the equivalent standalone reference building

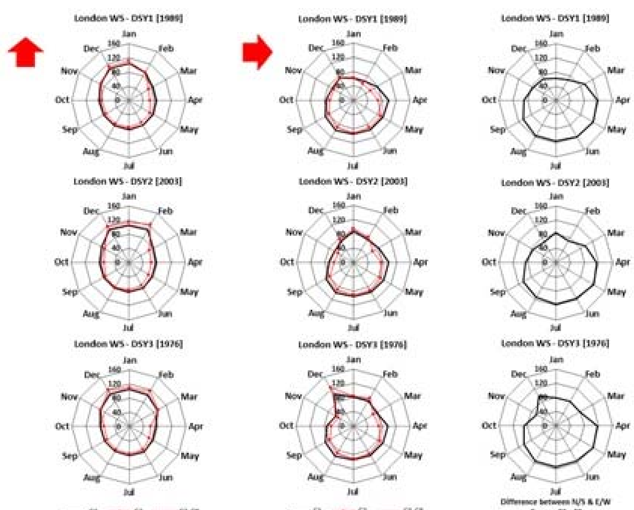

Figure 13: Monthly cooling loads for C1 to C8 for the North South orientated canyons (column 1), the East West orientated canyons (column 2), and the difference between these (column 3), for London Weather Station DSY weather files; C3-C8* are given as the average. Results are presented as the % difference against the equivalent standalone reference building